Alexandria Engineering Journal (2015) 54, 183–195

HOSTED BY

ELSEVIER

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Simulation of the behavior of pressurized underwater concrete

Ashraf Mohamed Heniegal [a], Alsaeed Abd El Salam Maaty [b], Ibrahim Saad Agwa [a],*

[a] *Civil Structures Dept., Faculty of Industrial Education, Suez University, Suez, Egypt*
[b] *Structures Engineering Dept., Faculty of Engineering, Tanta University, Tanta, Egypt*

Received 22 November 2014; revised 17 March 2015; accepted 22 March 2015
Available online 10 April 2015

KEYWORDS

Weight loss;
Water pressure;
Pressurized underwater concrete

Abstract Under-Water Concrete (UWC) contains Anti-Washout Admixtures (AWA) (0.0%, 0.2%, 0.3%, 0.4% and 0.5%) by weight of cement with cement contents (400, 450, 500 and 550 kg/m^3). All concrete mix contains silica fume and high-range water reducing (15% and 4%) respectively by weight of cement. The fine to steel slag coarse aggregate was 1:1. The concrete mix was tested for slump, slump flow, compressive strength and washout resistance using two test methods based on different principles. The first method is the plunge test CRDC61 which is widely used in North America, and the second method is the pressurized air tube which has been manufactured for this research and developed to simulate the effect of water pressure on washout resistance of underwater mix. The results of compressive strength test were compared to concrete cast underwater with that cast in air. Test results indicated that the use of an AWA facilitates the production of UWC mix with the added benefit of lower washout resistance. New technique of simulating pressurized UWC is reliable for detecting UWC properties. Adding AWA (0.3–0.5%) by weight of cement makes all mix acceptable according to Japanese Society of Civil Engineers.

1. Introduction

Underwater concrete is one special type of high performance concrete used in the past, present, and in the foreseeable future as long as there is need to construct bridges, with foundations in soil with high water levels, and almost all off- and on-shore structures. The term high performance concrete refers to concrete that performs particularly well in at least three key performance indicators: strength, workability, and service life. [1]. Successful casting of UWC can be achieved if sufficient attention is paid to the concrete mix design and placement techniques. Reduction in quality of the hardened concrete is mainly due to the washing out of cement and fine particles as well as segregation of coarse aggregates upon casting in water. Agitation of wet concrete by the action of surrounding water also causes washout of constituent elements [2]. Anti-washout UWC is by nature used essentially in aquatic environment and is increasingly finding most of its applications in marine environment rather than freshwater or river [3]. The anti-washout admixtures can

* Corresponding author.
E-mail addresses: ashraf_henigal@yahoo.com (A.M. Heniegal), saidmaaty@yahoo.com (A.A.E.S. Maaty), isaad_eng@yahoo.com (I.S. Agwa).
Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2015.03.017
1110-0168 © 2015 Faculty of Engineering, Alexandria University. Production and hosting by Elsevier B.V.

be made from various organic and inorganic materials. The two materials most commonly marketed as AWA are cellulose and gum. They act primarily by increasing the viscosity and the water retention of the cement paste [4]. Normally, underwater repairs pose a challenge to the contractor for various reasons, including the need to minimize washout of cement and fines during concrete placement. Dewatering is a solution, but it is costly. The cost of dewatering averages more than 40% of the total repair costs for hydraulic structures. An alternative to dewatering is placing concrete underwater, using a mix proportion containing higher amounts of cement, pozzolans such as silica fume, or AWA. Several projects have used this technology with great success [5]. The bond strength for the underwater repair concrete placed on the horizontal substrates with surfaces prepared using three various methods. Significant differences were found depending on the method of preparation of the concrete substrate surface. The best bond strength to the substrate, regardless of the applied pressure, was obtained for the substrates with sand-blasted surface. The bond strength to the horizontal sand-blasted surfaces was more than twice higher as compared to the repair concrete placed on the surfaces treated by low-pressure washing and much higher than in the case of the hammered surfaces. For the low-pressure washing hammering, a favorable effect of hydrostatic pressure on the bond strength of the repair concrete to the substrate was observed. However, for the sand-blasted surfaces, no distinct impact of hydrostatic pressure on the bond strength was found [6]. Concrete used for casting marine and offshore structures is generally referred to as UWC. The UWC develops lower in situ performance than other concrete cast and consolidated above water. Typical in situ residual compressive strengths reported in the literature were in the order of 80–90% for UWC cast using the tremie/hydrovalve technique [7]. The increase in demand for the ingredients of concrete is met by partial replacement of materials by the waste materials, which is obtained by means of various industries. Slag is a byproduct of metal smelting and hundreds of tons of it are produced every year all over the world in the process of refining metals and making alloys. Like other industrial byproducts, slag actually has many uses, and rarely goes to waste. It appears in concrete, aggregate road materials, as ballast, and is sometimes used as a component of phosphate fertilizer. In appearance, slag looks like a loose collection of aggregate with lumps of varying sizes [8]. The used electric arc furnace steel slag (EAFSS) in concrete aggregate helps in enhancing the cohesion between the aggregate particles and the surrounded cement mortar as well as the higher hardness of (EAFSS) due to the surface texture and shape [9].

The main objective of this paper was to provide guidelines for evaluating the efficiency of anti-washout admixtures for using in underwater concrete mix containing steel slag as the coarse aggregate. The paper aimed to highlight the effect of anti-washout admixtures, overhead pressures and cement contents on the workability, washout resistance, compressive strength loss, and the washout mass loss.

2. Experimental program

2.1. Materials

The materials that were involved in the experimental work were selected from local sources in Egypt. Ordinary Portland cement (CEM I 42.5N) was used. It is produced according to the Egyptian standards 4756/1-2007. The chemical compositions of cement are presented in Table 1. A silica fume was locally produced in Egypt containing more than 96% amorphous silicon dioxide (SiO_2). Its specific gravity and bulk density 2.15 and 0.345 are t/m^3 respectively. A high performance super plasticizer admixture of aqueous solution of modified polycarboxylate basis (Viscocrete-5930) was used to increase workability and viscosity (strong self-compacting behavior) of the concrete mix. Viscocrete-5930 complies with ASTM-C-494 types G, and BS EN 934 part 2: 2001. The dosage of the admixture was adjusted to minimize the water/cement ratio. Anti-washout admixtures consist of a powder-based welan gum developed specifically for using with underwater concrete construction and being as benefits for production of thixotropic mix with cohesive nature. A clean tap drinking water was used in all mix. Fine aggregate used was locally available in natural siliceous sand with a fineness modulus of 2.36 and specific gravity of 2.63. Steel slag coarse aggregate used local electric arc furnace steel slag that was obtained from Ezz steel industry factory in Suez. The EAFSS is a by-product during melting of steel scrap from the impurities and fluxing agents, which forms the liquid slag floating over the liquid crude iron or steel in electrical arc furnaces. Its specific gravity was 3.5, water absorption was 1.02% and bulk density was 1.92 t/m^3.

Table 1 Chemical properties of used cement, silica fume and steel slag coarse aggregate.

Cement		Silica fume		Steel slag coarse aggregate	
Chemical composition	Results by wt. (%)	Chemical composition	Results by wt. (%)	Chemical composition	Results by wt. (%)
SiO_2	21.0	SiO_2	96.00	SiO_2	13.10
Fe_2O_3	3.00	Fe_2O_3	1.45	Fe_2O_3	36.80
Al_2O_3	6.10	Al_2O_3	1.10	Al_2O_3	5.510
CaO	61.5	CaO	1.20	CaO	33.0
MgO	3.8	MgO	0.18	MgO	5.030
SO_3	2.5	K_2O	1.20	MnO	4.180
Na_2O	0.4	Na_2O	0.45	Cr_2O_3	0.775
K_2O	0.3	SO_3	0.25		
		H_2O	0.85		

Table 2 Concrete mix proportions.

Group	Mix	W/P	C (kg)	HRWR%	FA (kg)	SSCA (kg)	S.F%	AWA%
G1	M1	0.5	400	4	902	902	15	0
	M2				898	898		0.2
	M3				896	896		0.3
	M4				894	894		0.4
	M5				892	892		0.5
G2	M6	0.444	450	4	870	870	15	0
	M7				866	866		0.2
	M8				864	864		0.3
	M9				862	862		0.4
	M10				859	859		0.5
G3	M11	0.4	500	4	838	838	15	0
	M12				834	834		0.2
	M13				832	832		0.3
	M14				829	829		0.4
	M15				826	826		0.5
G4	M16	0.364	550	4	807	807	15	0
	M17				802	802		0.2
	M18				799	799		0.3
	M19				797	797		0.4
	M20				794	794		0.5

Where
W/P: water/binder ratio.
C: cement content.
HRWR: high-range water reducing.
FA: fine aggregates (sand).
SSCA: steel slag cores aggregate.
S.F: silica fume.
AWA: anti-washout admixtures.

2.2. Mix design, casting, and curing

The experimental program consists of four groups with a total number of twenty underwater-concrete mix. The test program was designed and arranged to determine the effect of two different parameters that are cement content and dosage of anti-washout admixtures. Table 2 gives a proportion of different concrete-mix materials. Concrete mix contains anti-washout admixtures (0.0%, 0.2%, 0.3%, 0.4% and 0.5%) by weight of cement and cement contents (400, 450, 500 and 550 kg/m^3). All concrete mix contains silica fume and high-range water reducing (15% and 4%) respectively by weight of cement. The fine-to- steel slag cores aggregate was 1: 1.

Fig. 1 shows underwater casting of concrete samples as twelve of 150 mm cubes were casted from each mix to evaluate compressive strength at both underwater casting and air casting conditions. The 150 mm cubic molds were placed underwater at a depth of 50 cm and the concrete was then poured from the top surface. The cubes were removed from the water tank. The cubes cast in air and underwater were left covered for approximately 24 h, then de-molded and cured in water at 20 + 3 °C. All specimens of the compressive strength tests were casted in molds without being mechanically consolidated. The cubes were tested for compressive strength at 7 and 28 days. The compressive strength test results were compared for concrete cast underwater with that cast normally (in air).

2.3. Mixing procedure

All batches were mixed according to the same procedure in an open pan mixer. The mixing sequence consisted of placing the wet steel slag as coarse aggregate and fine aggregate in the mixer and mixing for 1 min., and the cement and silica fume were then added and mixed for few seconds to obtain a homogeneous mix. The (AWA) powder was distributed into the mix followed by addition of water and HRWR. Once all constituents of the mix were added, the concrete was mixed for 3 min. following a 1 min rest, and the mixing was resumed for two additional 1 min.

2.4. Testing procedure

At the end of mixing, the slump, slump flow, weight loss, pH and compressive strength were determined. The weight loss of underwater concrete using two test methods based on different principles. The first method is CRDC61 [10]. Resistance of concrete mix to mass loss during underwater placement is measured by the U.S. Army Corps of Engineers Method CRD-C61 entitled test method for determining the resistance of freshly mixed concrete to wash out in water. Fig. 2 shows the test consists of placing freshly mixed concrete into steel perforated basket that is then dropped through a column of water approximately 1.7 m deep. The basket is raised to the surface and the cycle is repeated two more times, and the mass of the basket is measured at the beginning of and after the

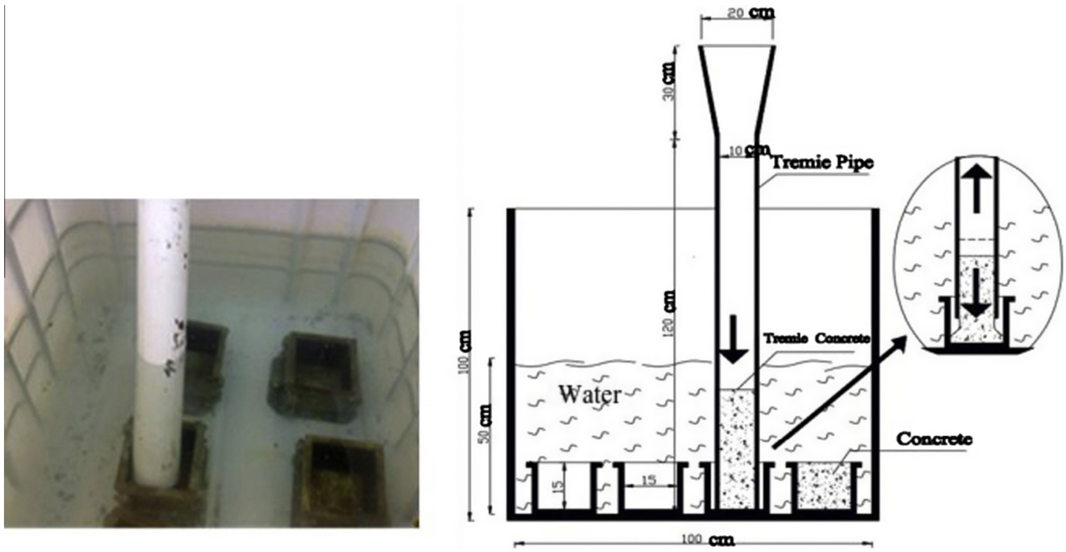

Figure 1 Underwater casting of concrete samples.

dunking cycles so that the cumulative mass loss in percent can be determined. Using this method, a concrete mix' resistance to mass loss during underwater placement can be measured and characterized.

The second method is the pressurized air tube [2]. Washout resistance is determined by simulation at different water heads using a pressurized steel column of 1500 mm height and 200 mm diameter. Fig. 3 shows the column was used to evaluate the effect of water head on washout resistance of underwater concrete. The testing procedure involved filling the column with water and dropping a fresh concrete sample placed in a perforated basket (similar to that used in CRD C61) to the bottom of the tube. The top cover was then tightly closed and an overhead air pressure introduced to simulate different water heads. Air pressure was monitored using two dial gauges of different ranges (0–9 bar) or (0–20 bar) connected to an air compressor, thus enabling the simulation of increased heads of water to 100 m. The steps used to simulate washout of plastic underwater concrete were as follows:

Figure 2 Apparatus and test for washout resistance.

Figure 3 Pressurized tube for washout resistance simulation of underwater.

A. Subjecting a sample of around 5 kg to free-fall to the bottom of the tube.
B. After tightly closing the top cover of the tube to prevent air leakage during pressure application, apply air pressure gradually until reaching the desired water head.
C. Keeping the desired pressure applied for 1 min.
D. Opening the air valves to release the pressure, and measure washout loss W.

The pH method was proposed in the recommendation for washout resistance of underwater concrete in Japan. The higher the pH the higher is the washout resistance [11].

3. Test results and discussion

The measured slump, slump flow, pH, weight losses and compressive strengths evaluated at 7 and 28 days age for underwater casting as well as air casting conditions of all mix are summarized in Table 3.

Table 3 Test results fresh and hardened underwater concrete.

Mix	Slump (mm)	Slump flow (mm)	pH	Weight loss (%)	7-Day compressive strength MPa			28-Day compressive strength MPa		
					F_{OW}	F_{UW}	F_{UW}/F_{OW}	F_{OW}	F_{UW}	F_{UW}/F_{OW}
M1	290	800	10.4	19	40	10.4	26	52.7	19	36
M2	270	630	9.6	12.9	32.5	20.9	64.3	40.9	27.5	67.3
M3	250	550	9.2	8.9	28	24.1	86	40	32	80
M4	250	470	9	5.3	26.7	24.2	90.4	39	35	89.7
M5	240	430	8.9	3.7	24.8	24.4	98.4	36	37.1	103
M6	280	760	10.3	18	45.3	12	26.5	57.3	22.5	39.2
M7	260	620	9.6	12.7	35.6	23	64.6	47.1	32.5	69
M8	250	520	9.1	7.8	33.1	28	84.6	42.3	37	87.40
M9	240	450	8.9	4.2	30.8	30.9	100.3	41.6	40	96.3
M10	230	400	8.8	2.70	30.2	32	106	40.9	43	105.2
M11	270	730	10	17.5	47	14	29.8	60	25.9	43.2
M12	260	600	9.5	12	36.7	27	73.6	52	40	76.7
M13	240	490	9	6.3	36	31.1	86.4	50	47	94
M14	230	420	8.9	4	34.4	33.9	98.5	49.8	49.6	99.5
M15	230	380	8.7	1.7	32	35.9	112.2	48	52	108
M16	270	700	10	17.20	50	17	34	66.7	30.9	46.3
M17	260	550	9.5	11.8	38	35.9	94.5	54	46	85.18
M18	240	480	9	6	37.6	39.6	105.3	54.4	54.7	100.4
M19	220	390	8.8	3	36.1	40.9	113.3	53.3	54.4	102
M20	200	350	8.7	1.6	34	40.9	120.3	50	56.7	113.3

Where
F_{OW}: compressive strengths for cast underwater.
F_{UW}: compressive strengths for cast normally (in air).
F_{UW}/F_{OW}: relative compressive strengths.

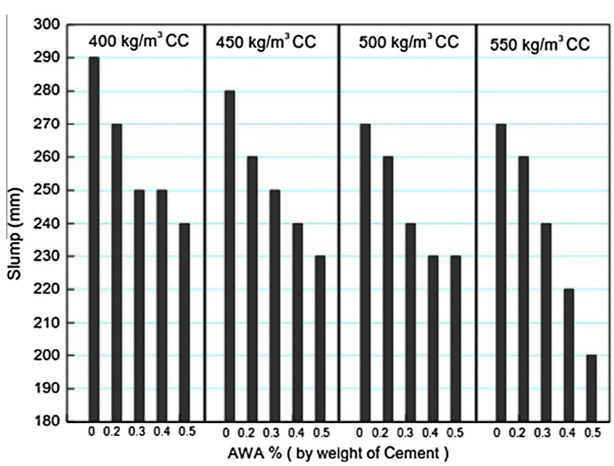

Figure 4 Effect of AWA and cement content on slump.

3.1. Slump

Slump test was used for measuring the consistency of fresh concrete. The test results are given in Table 3 and Fig. 4. It can be noted that slump value decreased as AWA dosage increased. The slump of the concrete mix with different AWA and cement content was approximately 250 ± 40 mm. This also agrees with the results given in [4]. The increase in AWA dosage seems to have a little impact on the slump values. For example, a concrete mix made with (0.0%, 0.2%, 0.3%, 0.4% and 0.5%) of AWA can develop slump values of (270, 260, 240 and 200 mm) respectively, for cement containing 550 kg/m^3.

3.2. Slump flow

The measured slump flow of all mix is summarized in Table 3 and Fig. 5 as shown in Fig. 6 group 4 slump flow for the different mix just after mixing. It can be noted that the slump flow values of underwater concrete decreased as AWA dosage increased which also agrees with the results given in [12,13]. This is attributed to AWA, which increases the viscosity and the water retention of concrete mix as well as the surface texture, shape, porosity and the heavy specific weight of the steel slag aggregate. For example, as a result of changing AWA of

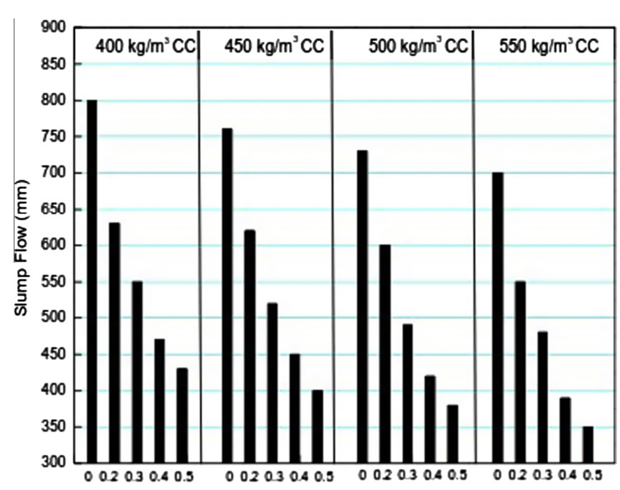

Figure 5 Effect of AWA and cement content on slump flow.

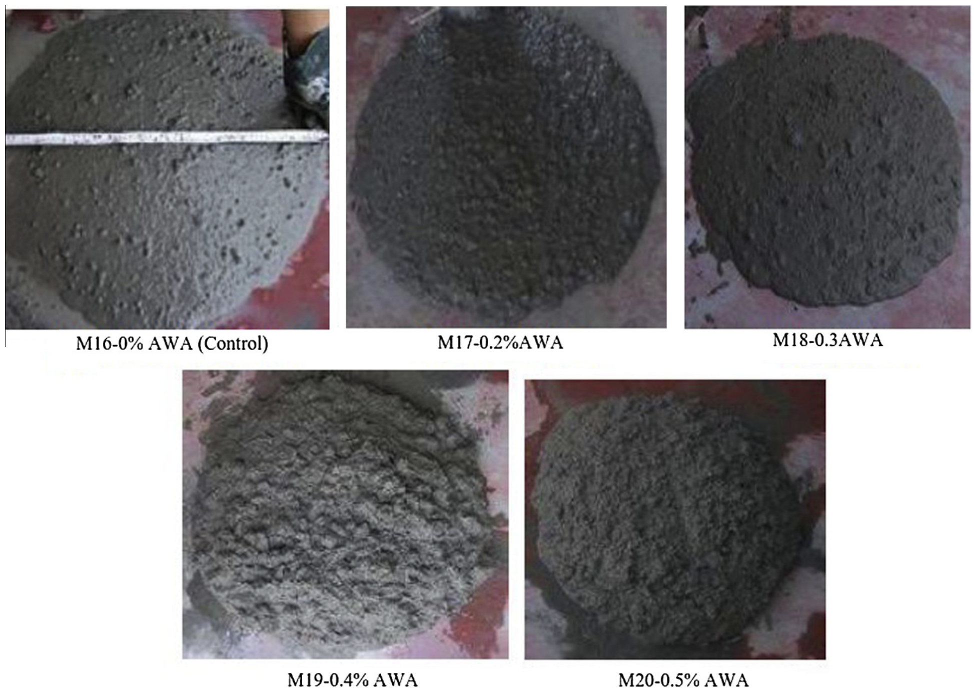

Figure 6 Group 4 slump flow for different mix just after mixing.

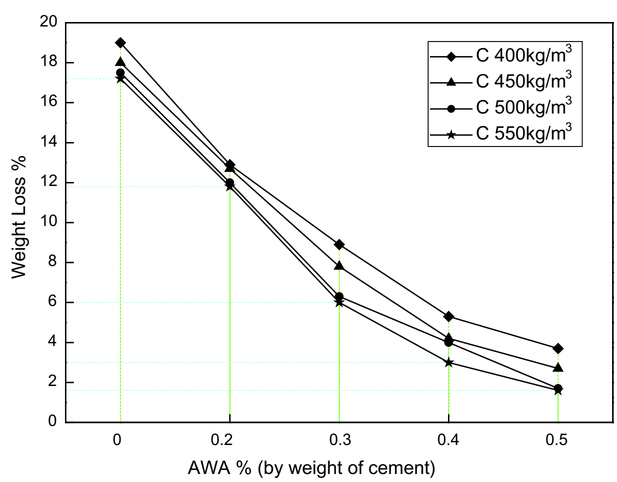

Figure 7 Effect of AWA and cement content on weight loss.

(0.0%, 0.2%, 0.3%, 0.4% and 0.5%) by weight of cement, the slump flow values were (700, 550, 480, 390 and 350 mm) respectively, for cement content 550 kg/m^3. The cited results indicate that for the developed mix, the flow diameter decreases with increasing the cement content and AWA. The AWA in concrete mix resulted in a substantial reduction in slump flow indicating that the presence of AWA tends to increase the viscosity of the mixture. Regarding viscosity, the importance of concrete viscosity is generated from the fact that increasing the viscosity maintains good suspension of the slag coarse aggregate during deformation of concrete and enhances the bond between the cementations paste and slag coarse aggregate thus minimizing the risk of segregation. For underwater applications, special attention should be directed to the viscosity because it governs the anti-washout characteristics of concrete.

3.3. Washout resistance determination using CRD C61

Table 2 summarizes the washout resistance determined using CRD-C61 weight loss and pH values. The weight loss was calculated of the sample's mass and expressed as a percentage of the initial mass of the sample using the following formula:

$$D = \frac{\mathrm{Mi} - \mathrm{Mf}}{\mathrm{Mi}} \times 100$$

where D = Weight loss%; Mi = Mass of sample before initial test; Mf = Mass of sample after each test.

3.3.1. Effect of AWA and cement content on weight loss

The measured weight loss of all mix is summarized in Table 3 and Fig. 7 showing the effect of AWA on weight loss. In general, weight loss decreased with the increase of AWA dosage. For example, as shown in Fig. 8 for the concrete mix group three, because of changing AWA from 0.0% to 0.5% by weight of cement the weight loss decreased from 17.5% to 1.7% respectively. Enhancement in this case is attributed to the use of AWA which retains part of mixing water and increases the viscosity of the liquid phase of the concrete. On the other hand, the weight loss decreased with the increase of cement contents. For example, as a result of changing cement contents from 400 to 550 kg/m^3, weight losses can be developed from 8.9% to 6% respectively at 0.3% of AWA. This may be attributed to the relative increase of cement paste volume when the cement content and AWA were increased in the mix.

Figure 8 Appearance of fresh concrete after submerging in water.

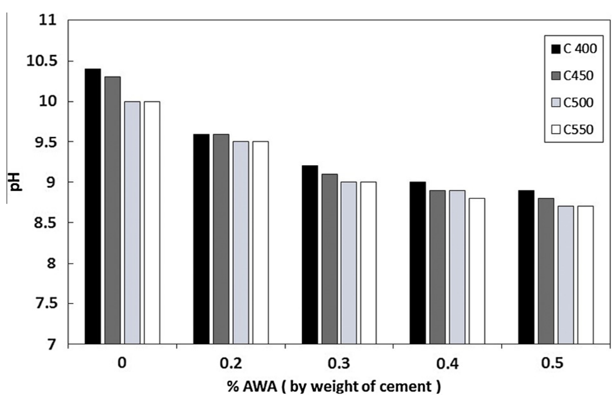

Figure 9 Effect of AWA and cement content on pH.

3.3.2. *Effect of AWA and cement content on pH value*

The measured pH value of all mix is summarized in Table 3 and Fig. 9. The pH value is measured after weight losses. This value was recorded as a second indicator for washout-resistance. As shown in Fig. 10 for the concrete mix group two, pH value decreased as AWA dosage increased. For example, as a result of changing AWA of (0.0%, 0.2%, 0.3%, 0.4% and 0. 5%) by weight of cement, the pH values were (10.3, 9.6, 9.1, 8.9 and 8.8) respectively, for cement content 450 kg/m^3. On the other hand, for mixes containing 0.2% of AWA, as a result of changing cement contents (400, 450, 500 and 550 kg/m^3), pH values were (9, 8.9, 8.9 and 8.8) respectively. This also agrees with the results given in [14].

3.4. *Washout-resistance determined (pressurized air tube)*

Through the variation of placement depth (simulated by varying the overhead pressure in the pressurized tube), weight loss and pH can be determined. The overhead pressure increased (2.5, 5 and 10 bars), corresponding to (25, 50 and 100 m) of water head. The measured weight loss and pH of twelve concrete mix are summarized in Table 4.

3.4.1. *Effect of water head and AWA on weight loss*

The measured weight loss of all mixes is summarized in Table 4 and Fig. 11 which shows the Effect of water head and AWA on weight loss for different cement contents. In general, the increase in weight loss with water head is shown to increase sharply when the applied pressure exceeds a certain threshold water head. This also agrees with the results given in [2]. For underwater concrete mix containing 400 kg/m^3 of cement, as a result of changing overhead pressure of (2.5,5 and 10 bars) corresponding to (25, 50, and 100 m) of water head, the weight loss was (7%, 7.5% and 13.4%) respectively, at 0.2% of AWA. On the other hand, the weight loss decreased as AWA dosage increased. This is attributed to that AWA which increased the

Figure 10 Effect of AWA on pH value measuring.

Table 4 Washout resistance determined (pressurized air tube).

Mix	Depth (M)	pH	Before submersion (kg)	After submersion (kg)	Weight loss (%)
M1	25	9.6	5.22	4.61	11.7
	50	9.8	5.19	4.44	14.5
	100	10.2	5.30	4.30	18.9
M2	25	9	5.61	5.22	7
	50	9.1	6	5.55	7.5
	100	9.7	6.12	5.30	13.4
M3	25	8.9	5.89	5.67	5
	50	9	5.89	5.55	5.8
	100	9.5	5.64	5	11.3
M4	25	8.9	5.54	5.35	3.4
	50	8.9	5.7	5.51	4.5
	100	9.1	5.64	5.22	7.5
M6	25	9.2	5.71	5.15	9.8
	50	9.5	5.6	4.9	12.5
	100	9.8	5.65	4.85	14.2
M7	25	8.9	5.70	5.45	4.5
	50	9	5.46	5.1	6.6
	100	9.5	5.82	5.21	11.7
M8	25	8.8	5.52	5.33	3.4
	50	9	5.56	5.25	5.6
	100	9.2	6.08	5.57	8.4
M9	25	8.8	5.71	5.55	2.8
	50	8.9	5.86	5.63	3.9
	100	9.1	5.51	5.1	7.4
M11	25	9.1	5.22	4.75	9
	50	9.4	5.2	4.6	11.5
	100	9.6	5	4.37	12.6
M12	25	8.9	5.8	5.55	4.3
	50	9.1	5.74	5.3	7.7
	100	9.1	5.98	5.45	9
M13	25	8.8	5.62	5.45	3.2
	50	8.9	5.7	5.42	4.9
	100	9.1	6.23	5.78	7.2
M14	25	8.7	5.5	5.35	2.7
	50	8.9	5.59	5.38	3.8
	100	9.3	5.78	5.4	6.6

viscosity and the water retention of concrete mix. For example, as a result of the AWA change from 0.0% to 0.4% by weight of cement, the weight loss was from 18.9% to 7.5% respectively, at overhead pressure 10 bar corresponding to water head 100 m, which clearly indicates that washout is directly dependent on water depth at the casting point. Concrete mix containing 0.3% of AWA, as a result of changing cement content from 400 to 500 kg/m^3, can develop weight loss from 11.3% to 7.2% respectively at overhead pressure 10 bar corresponding to water head 100 m. This can be related to the relative increase of cement paste volume when the cement content is increased in the mix.

3.4.2. Effect of water head and AWA on pH value

The measured pH value of all mix is summarized in Table 4 and Fig. 12. In general, the increase in pH value relates to water head increase. For underwater concrete mix containing 450 kg/m^3 of cement content, as a result of changing overhead pressure 2.5, 5 and 10 bars corresponding to water head 25, 50, and 100 m, the pH value was 8.8, 8.9 and 9.1 respectively at 0.4% of AWA by weight of cement.

From Fig. 12, the pH value decreased as cement content increased. For example, for concrete mix without AWA, and because of changing cement contents from 400 to 500 kg/m^3, this can develop pH from 9.8 to 9.4 respectively at overhead pressure 5 bar corresponding to a water head 50 m.

3.4.3. Relation between standard weight loss and weight loss determined by pressurized air tube

The variations of weight loss determined by CRD-C61 with respect to the threshold water head and the corresponding weight loss determined by simulation are plotted in Fig. 13. Concrete with a lower weight loss can be casted at a deeper water depth or higher threshold depth. For mix made with

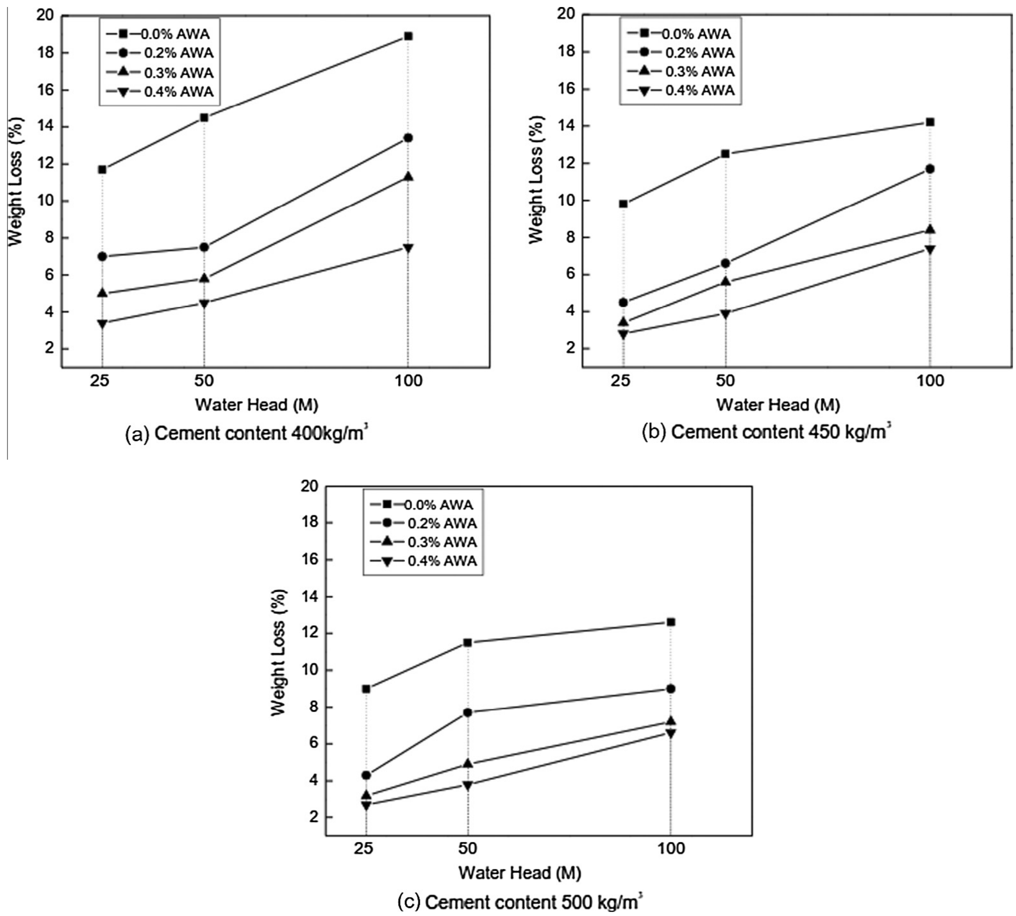

Figure 11 Relation between weight loss and water head (M).

400 kg/m^3 cement content, it can be noticed when adding AWA from 0.0% to 0.4% by weight of cement that there is a decrease in weight loss determined by CRD C61 from 19% to 5.3% respectively. On the other hand, as a result of the increase in threshold water head 25, 50 and 100 m, the corresponding weight loss at these values was (11.7–3.3%), (14.5–4.5%) and (18.9–7.5%) at AWA from (0.0% to 0.4%) respectively.

3.5. Unit weight

The unit weight of the hardened concrete was determined for the concrete cubes just before carrying out the compression test. The unit weight of the underwater concrete containing steel slag as the coarse aggregate varied from 2400 kg/m^3 to 2655 kg/m^3. The higher unit weight of the steel slag coarse aggregate concrete is attributed to the higher specific gravity of the steel slag coarse aggregate.

3.6. Compressive strength

The mechanical properties of underwater concrete were investigated in terms of compressive strength at 7 and 28 days. Test specimens made underwater are produced by placing concrete into water 500 mm deep. The compressive strength test results for concrete cast underwater were compared with strengths determined on cubes cast normally (in air) and are summarized in Table 3. The strength at each age was measured for three specimens and averaged.

3.6.1. Effect of AWA on the compressive strength

Fig. 14a and b shows the strength at 28 days for the air placed and water placed specimens at different cement contents, respectively. As expected, the concrete compressive strength of test specimens casted in the air is generally greater than that of cast underwater. This also agrees with the results given in [4,12]. It is attributed to the contamination of fresh concrete resulting from water erosion.

Generally, compressive strength of test specimens made in air (casting in air) is lowered by an increase of the amount of AWA. This is attributed to the amount of AWA increased that can result in an increase in air-entrainment that will tend to lower the compressive strength. For mix made with 400 kg/m^3 cement content, as a result of changing AWA of (0.0%, 0.2%, 0.3%, 0.4% and 0. 5%) by weight of cement, the compressive strength of the concrete was (52.7, 40.9, 40, 39 and 36 N/mm^2) respectively. On the other hand, compressive strength of test specimens made in water (casting in water) increased by an increase of the amount of AWA. For example, because of changing AWA of (0.0%, 0.2%, 0.3%, 0.4% and 0. 5%) by weight of cement, the compressive strength of the concrete was (19, 27.5, 32.8, 35 and 37.1 N/mm^2) respectively. For

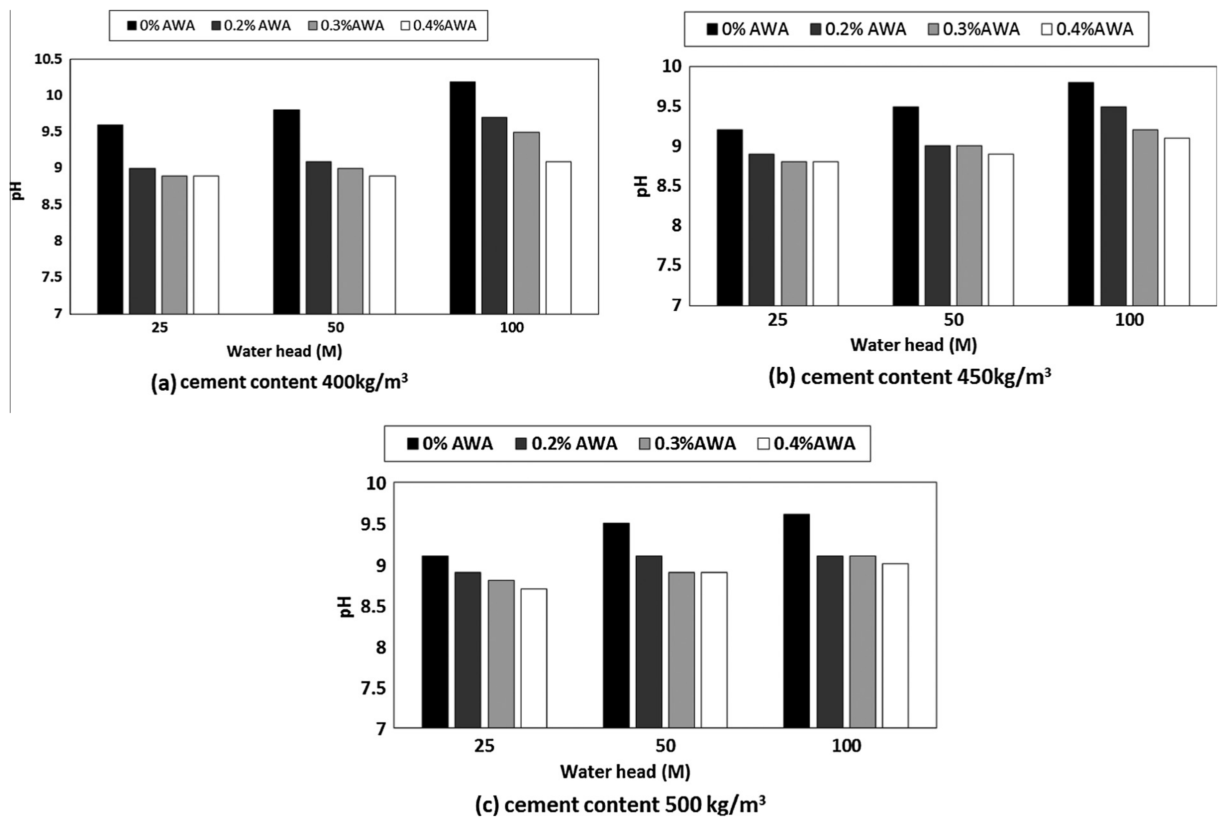

Figure 12 Relation between pH and water head (M).

mix made with 450 kg/m^3 cement content, it can be noticed that the compressive strength of test specimens made in air (before submersion) is lowered by an increase of the amount of AWA. For example, as a result of changing AWA from (0.0% to 0. 5%), the compressive strength dropped from (57.3 to 40.9 N/mm^2) respectively. This means that greater dosages of AWA resulted in a reduction of concrete compressive strength. Same behavior was also reported by others [13]. On the other hand, for underwater concrete (after submersion), the compressive strength highly decreased in concrete mix without AWA, but the compressive strength has also increased when the amount of AWA increased. For example, because of changing AWA from (0.0% to 0. 5%) the compressive strength went from (22.5, to 43 N/mm^2) respectively.

3.6.2. *Effect of cement content with 15% silica fume on the compressive strength*

The measured compressive strength for the air placed and water placed of all mix is summarized in Table 3. For mix without AWA made in air (casting in air), it was shown a high increase in the compressive strength (52.7, 57.3, 60 and 66.7 N/mm^2) at cement contents (400, 450, 500 and 550 kg/m^3) respectively. This may be attributed to the relative increase of cement paste volume when the cement content is increased in the mix. Furthermore, mix was-prepared with higher cement contents. In addition, the enhancement in the compressive strength due to the increase in cement content for mix with 15% silica fume increased due to the pozzolanic reaction of the used silica fume. On the other hand, for mixes without AWA made in water, the compressive strength highly decreased , as a result of changing cement contents (400, 450, 500 and 550 kg/m^3) was (19, 22.5, 25.9 and 30.9 N/mm^2) respectively. For mix with AWA 0.3%, as a result of changing cement contents from (400 to 550 kg/m^3), compressive strength made in air was (40–54.4 N/mm^2) respectively. On the other hand, the compressive strength made in water was (32–54.7 N/mm^2) respectively.

3.6.3. *Relation between relative compressive strength and weight loss*

Fig. 15 shows the graphical relation between relative compressive strength and weight loss. It can be noted that the relative compressive strength increases with weight loss decrease. This also agreed with the results given in [12–15]. From Fig. 15, it is indicated that the relative compressive strength is directly dependent on weight loss. For example, adding AWA reduced weight loss from 19% to 1.6%; hence, relative compressive strength increased from 36% to 113.3% for different AWA and cement contents. This can be attributed to the relative loss of cement paste associated with a potential infiltration of water inside the concrete. This suggests that concrete parameters should be appropriately selected and proportioned to reduce weight losses and thereby maintain adequate relative compressive strength [2]. The compressive strength of test specimens made in water (casting in water) to those made in air (casting in air) increases as the amount of AWA and cement content increases. For mix made with 400 kg/m^3 cement content, as a result of changing AWA (0.0%, 0.2%, 0.3%, 0.4% and 0.5%) by weight of cement, the relative compressive strength was (36%, 67.3%, 80%, 89.7% and 103%) corresponding

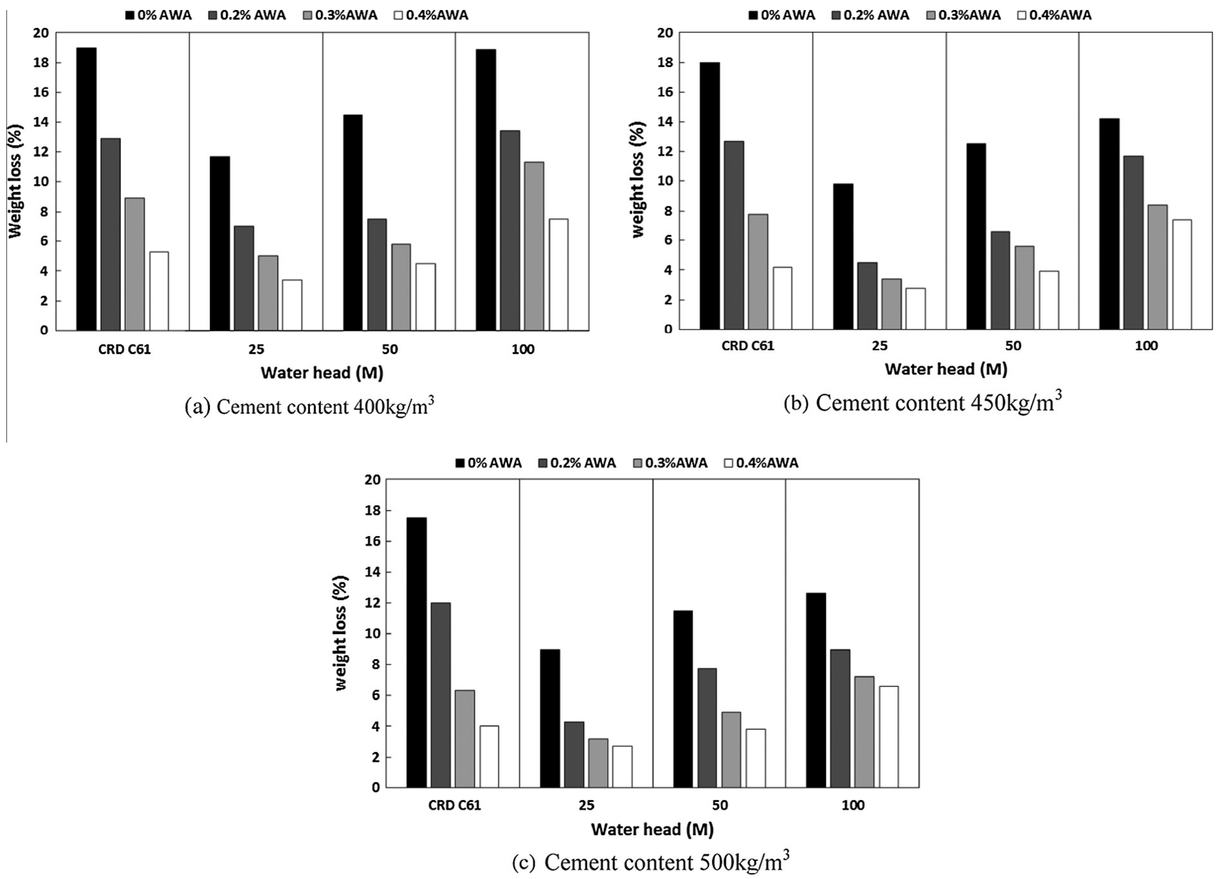

Figure 13 Relation between standard weight loss CRD-C61 and weight loss determined by pressurized air tube.

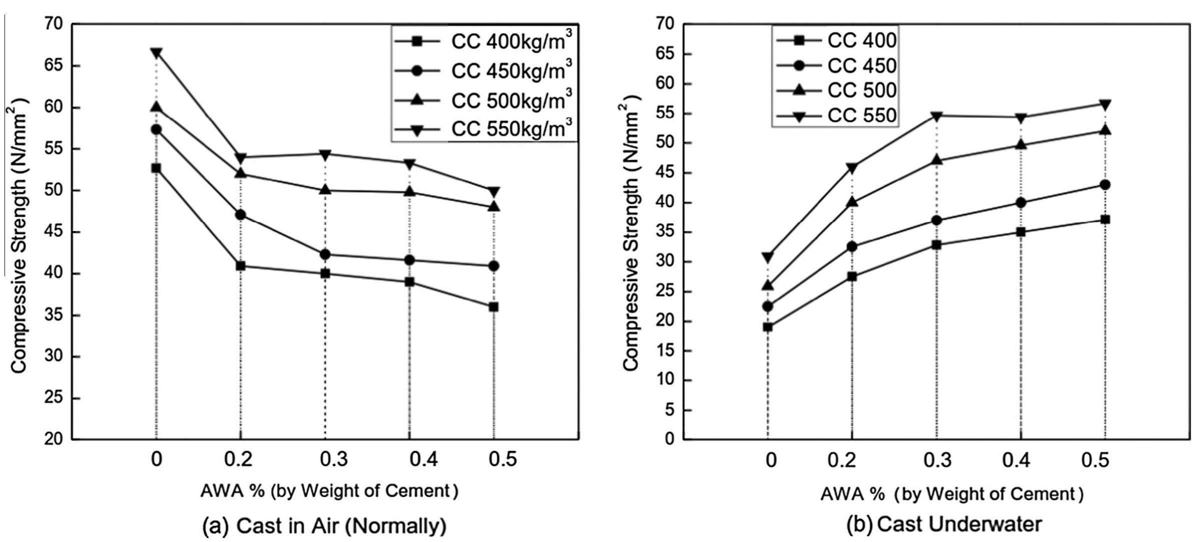

Figure 14 Relation between compressive strength and percentage of AWA at 28 day.

to a weight loss (19%, 12.9%, 8.9%, 5.3% and 3.7%) respectively. On the other hand, for mix made with (0.3%) of AWA, because of changing cement contents (400, 450, 500 and 550 kg/m^3), the relative compressive strength was (80%, 87.40%, 94% and 100.4%) corresponding to a weight loss (8.9%, 7.8%, 6.3% and 6%) respectively.

3.6.4. Relation between relative compressive strength and pH value

Finally, the graphical relation between relative compressive strength and pH value for different cement contents and AWA is shown in Fig. 16 as it can be noted that the increase of relative compressive strength is with pH value decrease,

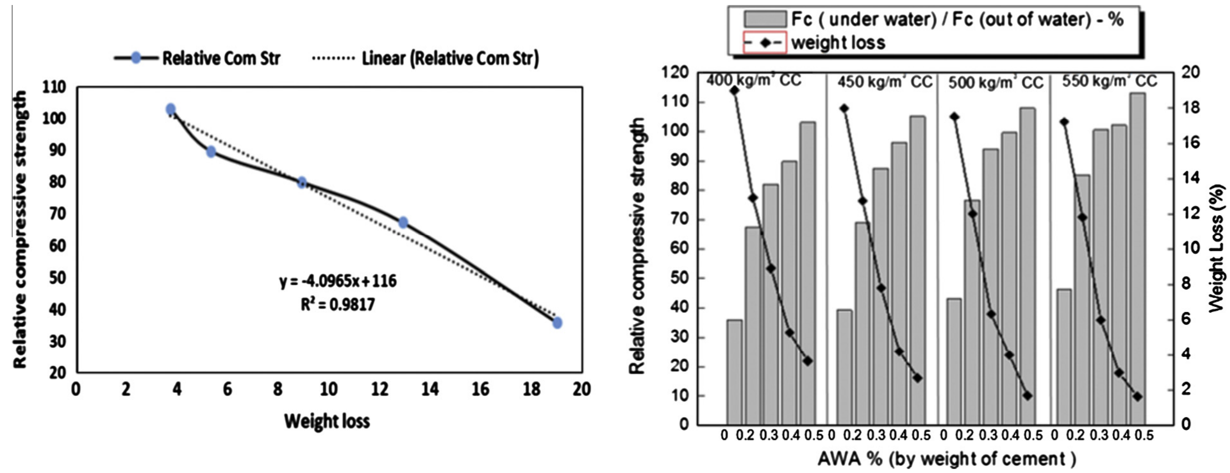

Figure 15 Relation between relative compressive strength and weight loss.

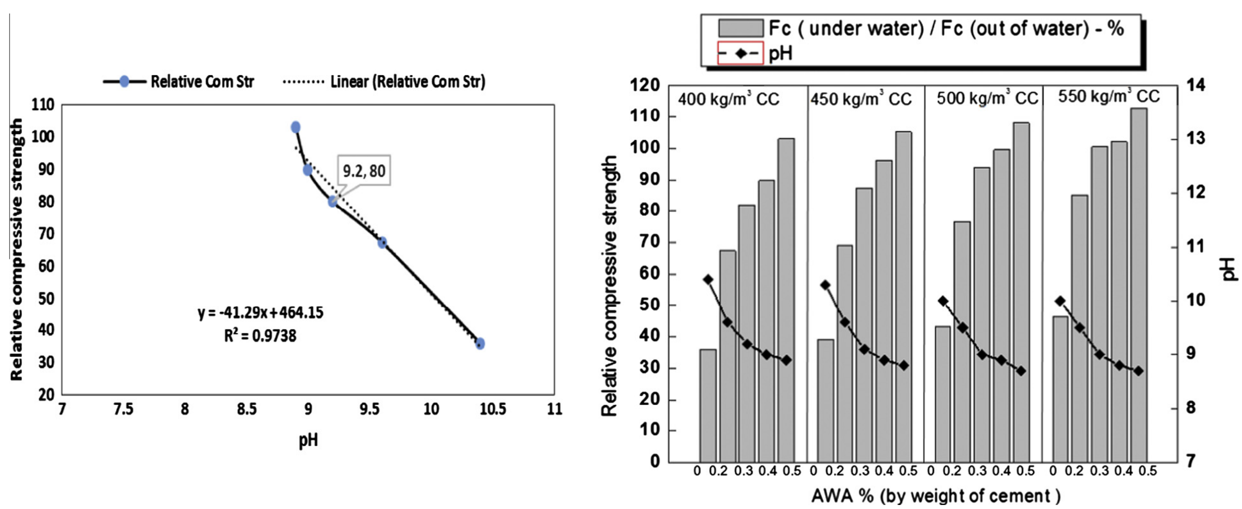

Figure 16 Relation between relative compressive strength and pH.

indicating that the relative compressive strength is directly dependent on pH. For example, an increase in pH from 8.7 to 10.4 led to a reduction in (fc underwater/fc outwater) from 113.3% to 36% respectively, for different AWA and cement contents. From Fig. 16 for mix made with 450 kg/m^3 cement content, as a result of changing AWA (0.0%, 0.2%, 0.3%, 0.4% and 0. 5%) by weight of cement, the relative compressive strength was (39.2%, 69%, 87.40%, 96.3% and 105.2%) corresponding to a pH value (10.3, 9.6, 9.1, 8.9 and 8.8) respectively. On the other hand, for mix made with (0.2%) of AWA, and because of changing cement contents (400, 450, 500 and 550 kg/m^3), the relative compressive strength was (67.3%, 69%, 76.7% and 85.2%) corresponding to a pH value (9.6, 9.6, 9.5 and 9.5) respectively.

4. Conclusions

Anti-washout admixtures were successfully used to enhance the resistance of pressurized underwater concrete to water erosion and segregation. Based on the results of the experimental work presented in this paper, the following conclusions are drawn:

- Slump and slump flow values of underwater concrete decreased as AWA dosage increased, in which concrete mix' slump values ranged from (270 to 290 mm) without AWA whereas slump with AWA reached 200 mm. Flow diameters ranged from (700 to 800 mm) without AWA whereas it reached 350 mm with AWA.
- Segregation of the concrete mix was exhibited due to the heavy specific weight of the steel.
- Slag aggregate without AWA whereas no segregation of mix with AWA.
- All concrete mix (0–0.2% AWA) was self-compacting concrete but did not achieve the Japanese Society of Civil Engineers (JSCE) standards that recommended a minimum of 70% relative compressive strength.
- The weight loss decreased with the increase of the dosage of AWA. As a result of changing AWA (0.0–0. 5%) by weight of cement, the average weight loss was about (17.9–2.4%) respectively.
- As a result of changing overhead pressure from (2.5 to 10 bars) corresponding to (25–100 m) of water head, the weight loss increased from (7% to 13.4%) respectively.

- The pH decreased with the increase of the dosage of AWA. As a result of changing AWA (0.0–0. 5%) by weight of cement, the average pH value was about (10.2–8.8) respectively.
- The compressive strength ratio of test specimens made underwater to those made in air increased as the amount of AWA increased. As a result of changing AWA (0.0%, 0.2%, 0.3%, 0.4% and 0.5%) by weight of cement, the relative compressive strength was (36%, 67.3%, 80%, 89.7% and 103%) corresponding to a weight loss (19%, 12.9%, 8.9%, 5.3% and 3.7%) respectively.

References

[1] S. Mindess, Developments in the formulation and reinforcement of concrete, A volume in Wood head Publishing Series in Civil and Structural Engineering, first ed., 2008, pp. 136–153.
[2] J.J. Assaad, Y. Daou, H. Salman, Correlating washout to strength loss of underwater concrete, J. Inst. Civ. Eng. 106 (6) (2011) 529–536.
[3] H.Y. Moon, K.J. Shin, Evaluation on steel bar corrosion embedded in antiwashout underwater concrete containing mineral admixtures, Cem. Concr. Res. 36 (2006) 521–529.
[4] M. Imam, The use of anti-washout admixtures in underwater concrete, in: Egyptian Engineers Association of the 2nd Conference, Riyad, 15–17 May, 2010.
[5] M.A. Bury, C.K. Nmai, G. Amekuedi, J. Bury, Unique applications of a cellulose-based antiwashout admixture, Concr. Int. 23 (4) (2001) 23–28.
[6] E. Horszczaruk, P. Brzozowski, Bond strength of underwater repair concretes under hydrostatic pressure, J. Constr. Build. Mater. 72 (2014) 167–173.
[7] J.J. Assaad, C.A. Issa, Bond strength of epoxy-coated bars in underwater concrete, J. Constr. Build. Mater. 30 (2012) 667–674.
[8] P.S. Kothai, R. Malathy, Utilization of steel slag in concrete as a partial replacement material for fine aggregates, Int. J. Innovative Res. Sci., Eng. Technol. 3 (2014) 11585–11592.
[9] M.A. Khafaga, W.S. Fahmy, M.A. Sherif, A.M.N. Abdel Hamid, Properties of high strength concrete containing electric arc furnace steel slags aggregate, J. Eng. Sci. (2014) 582–608. Assiut University, Egypt.
[10] US (United States Army Corps of Engineers) CRD -C61-89A, Test method for determining the resistance of freshly-mixed concrete to washing out in water. US Army Experiment Station, Vicksburg, MS, 1989, pp. 1–3.
[11] Japan Society of Civil Engineers, Recommendations for design and construction in anti-washout underwater concrete, Concr. Libr. JSCE (67) (May 1991) 89 p.
[12] E.E. Ali, E.A. Kattab, Self-flowing under-water concrete mixtures with and without anti-washout admixture, J. Eng. Res. (2013). Azhar University, Egypt.
[13] K.M. Yousri, Self-flowing underwater concrete mixtures for high-rise structures, in: International Conference on Multi-Purpose High Rise Towers and Tall Buildings of the 7th, Conference, Dubai, UAE, 10–11 December, 2005.
[14] A.M. Heniegal, Behavior of underwater self-compacting concrete, J. Eng. Sci. 40 (4) (2012) 1005–1023. Assiut University, Egypt.
[15] J.J. Assaad, C.A. Issa, Mechanisms of strength loss in underwater concrete, Mater. Struct. 46 (2013) 1613–1629.